ARTIFICIAL SATELLITES, Vol. 48, No. 1 – 2013
DOI: 10.2478/arsa-2013-0002

SPECTRAL ANALYSIS OF BOROWIEC SLR DATA FOR SPIN DETERMINATION OF GEODETIC SATELLITE EGP

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ABSTRACT. Borowiec 10 Hz Satellite Laser Ranging (SLR) station is capable to measure spin of the Japanese Experimental Geodetic Satellite (EGP). Spectral analysis of 391 passes measured from March 10, 1994 to November 27, 2009 gives frequency signal representing the 3rd and the 6th harmonics of the satellite spin rate. Analysis of this signal, corrected for the apparent effects, indicates en exponential slowing down of the satellite: the spin rate decreases according to the equation $f = 671.115907 \cdot \exp(-4.08324 \times 10^{-5} \cdot D)$ [mHz], where D is a day after launch. More than 15 years of the SLR measurements allowed investigating the initial spin rate of the satellite f_{ini} = 671.116, RMS = 0.203 [mHz] (initial spin period T_{ini} = 1.49006, RMS = 0.0007 [s]).

Keywords: space geodesy, Satellite Laser Ranging, EGP, Ajisai, geodetic satellite, satellite spin

1. INTRODUCTION

1.1. THE EXPERIMENTAL GEODETIC SATELLITE

The Japanese Experimental Geodetic Satellite (Ajisai, Fig. 1) was launched on August 12, 1986 (MJD_{Launch} = 46654) by the National Space Development Agency (NASDA), currently reorganized as Japan Aerospace Exploration Agency (JAXA). The initial objective of the mission was accurate position determination of geodetic fiducial points on the Japanese Islands. This fully passive satellite is equipped with 1436 corner cube reflectors (CCRs) for SLR, placed on 120 panels and arranged in the form of 15 rings around the symmetry axis (Fig. 2). Ajisai is also equipped with 318 mirrors, used to determine its angular position in reference to the stars (Sasaki et al., 1987). The mirrors have also been used for photometric measurements of Ajisai spin (Otsubo et al., 1998).

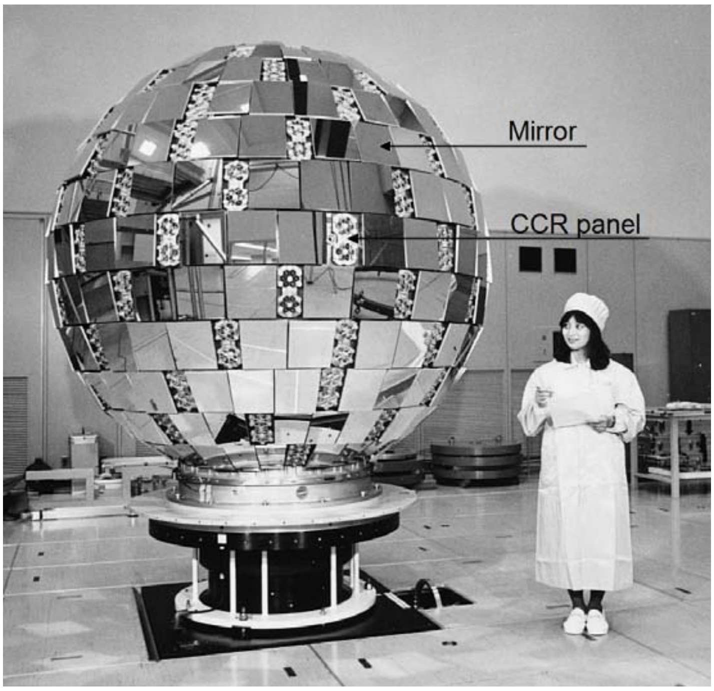

Fig. 1. Ajisai (courtesy of JAXA).

The satellite was placed in a quasi-circular orbit at a height of 1490 km (inclination 50º). The spin parameters of Ajisai have been investigated scientifically (Kucharski et al., 2009b, 2010a, 2010b, Otsubo et al., 1998; 2000) showing an exponential decrease of the spin rate and a precession of its spin axis. The knowledge of the spin parameters of the passive satellites allows for the investigation and improvement of physical models of the perturbing forces and torques which are of magnetic, gravitational and non-gravitational nature (Andrés et al., 2004, Bertotti et al., 1991). Such improved models are used for precise orbit determination (Otsubo et al., 1999; 2003) and can increase the accuracy of the determination of SLR station positions and of geodynamical parameters.

1.2. AJISAI CORNER CUBE REFLECTOR ARRAY

The CCR panels are distributed in a form of 15 rings over the satellite body (Fig. 2). The array has a 120º longitudinal symmetry. The panels of the 11 largest rings ($R_{-5}..R_5$) are separated by smaller and larger gaps, only the 4 pole rings show identical gaps between the panels. This symmetry and the larger gaps allow identification of the individual CCR panels; e.g. on the equator ring (R_0) there are three sets of four panels separated by three relatively large gaps. The array holds 5 rings with 12 CCR panels: R_{-2}, R_{-1}, R_0, R_1, R_2; 4 rings with 9 CCR panels: R_{-4}, R_{-3}, R_3, R_4; 2 rings with 6 CCR panels: R_{-5}, R_5; and 4 rings with 3 CCR panels: R_{-7}, R_{-6}, R_6, R_7.

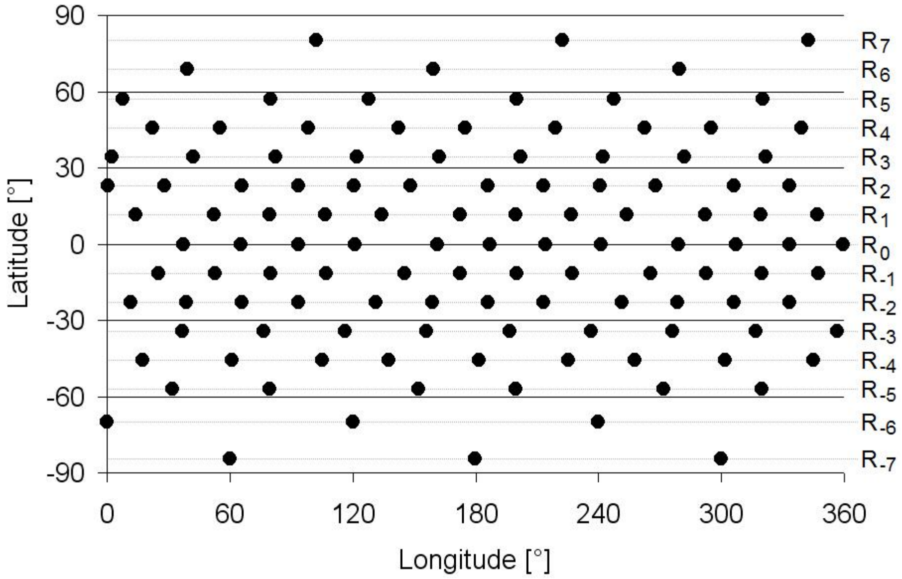

Fig. 2. Distribution of the CCR panels over the satellite surface. The CCR array consists of 15 rings $R_{-7}...R_7$; R_0 is an equator ring.

2. SPIN MEASUREMENTS OF THE GEODETIC SATELLITES

2.1. TECHNIQUES FOR SPIN MEASUREMENTS

Many of the geodetic satellites are fully passive, spherical bodies. Usually they are equipped with CCRs only. The only exception is Ajisai, which is additionally equipped with mirrors. The usage of passive elements only restricts possible spin detection techniques to photometry and SLR.

For the fast spinning (several dozen rotations during one pass) satellites with CCRs or mirrors arranged in the form of the rings, photometry is the appropriate technique. It determines epoch times of glints caused by sunlight reflected by the outer surfaces of the CCRs, or by the dedicated mirrors of Ajisai. Measuring the glint frequency allows identification of the particular ring which is reflecting light at a given epoch. During a single pass the attitude of the satellite with respect to the observation site on the Earth is changing, thus the consecutive rings of the satellite will be the source of the glints. By finding the epoch of change from one ring to another it is possible to determine the spin axis orientation of the body (Otsubo et al., 1998; 2004). This method allows also for spin period determination. The photometry however is restricted to night observations only, when the satellite is illuminated by the Sun.

The standard 10 – 20 Hz SLR system cannot measure spin axis orientation, but it is suitable for spin period determination of the geodetic satellites (Bianco et al., 2001, Otsubo et al., 2000). The laser pulses transmitted from an SLR station are reflected by CCRs back to the receiver telescope of the SLR system. The surface of the spinning satellite is scanned by these laser pulses, and the motion of the CCRs engraves a frequency signal on the SLR data. This signal can be obtained by spectral analysis of the unequally spaced return signals. SLR can measure spin periods of the satellites during day and night, regardless of the Sun – satellite – station geometry (as it is with photometry), and without any additional equipment.

The sub-mm precision Graz kHz SLR system makes possible identification of the range measurements to a single CCR of a satellite, what allowed spin determination of:

- slowly spinning LAGEOS-1, LAGEOS-2 (Kucharski et al., 2007 , Kucharski et al., 2009a),
- High Earth Orbiting Etalon-1 and Etalon-2 (Kucharski et al., 2008),
- fast spinning Ajisai (Kirchner et al., 2007; Kucharski et al., 2009b, 2010a, 2010b),
- active Gravity Probe – B, equipped with a small CCR panel,
- the first spherical lens type satellite BLITS (Kucharski et al., 2011).

2.2. SPIN MEASUREMENTS WITH BOROWIEC SLR SYSTEM

Borowiec SLR system (Poland) operates with 10 Hz repetition rate Nd:YAG laser installed on September 21, 1991 (half pulse width 40 ps, energy per pulse 20 mJ). The station operates at night time only, when the high energy per pulse allows reaching returns rate of about 80 % (more than 5000 range measurements per pass). The single range measurement is calculated as a time-of-flight of a single laser pulse. This time is measured between the start and stop events generated by laser photoelectrons. The start event is generated by outgoing laser pulse when it leaves the SLR system. The laser photons reflected by the CCRs of the satellite arrive into the receiving telescope of the SLR system where they are focused on the photodetector. The detection package of the Borowiec SLR system is based on a photomultiplier (PMT) and reacts to multi-photon signal for low Earth orbiting satellites like Ajisai. In order to generate the stop event the PMT needs to collect certain amount of energy reflected by the multiple CCRs from the nearest part of the satellite surface.

After every pass the range measurements are processed and the range residuals (observed minus predicted range) are calculated and spectrally analyzed in order to retrieve frequency signal engraved to the data by the spinning satellite. The Lomb method of spectral analysis was suggested (Otsubo et al., 2000) as an alternative to the Fast Fourier Transform (FFT), to allow for analysis of non-equally spaced data, as it is the case for SLR measurements. Although the FFT could be used with the data gaps interpolated, this could introduce unwanted frequencies. Therefore the Lomb method is preferred.

3. SPIN DETERMINATION

In order to calculate spin rate of Ajisai we used 391 night time passes measured by Borowiec SLR station from March 10, 1994 to November 27, 2009. For every pass the range residuals were calculated and spectrally analyzed with the Lomb algorithm.

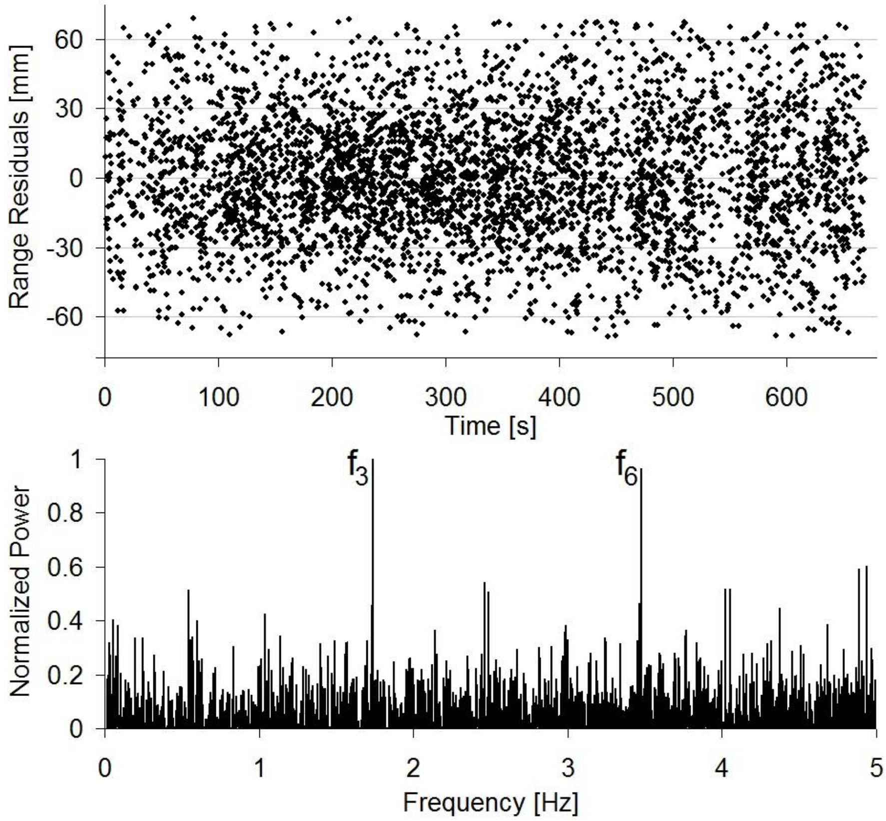

Fig. 3. Top: range residuals of Ajisai, pass measured on July 19, 1996. Bottom: spectra obtained by frequency analysis of the range residuals; peak f_3 = 1.7384 Hz, f_6 = 3.4762 Hz.

Fig. 3-top presents range residuals of Ajisai pass measured on July 19, 1996. During 671 seconds of observation – 4274 range measurements were collected and recalculated into range residuals (RMS = 27.6 mm). Spectral analysis of the residuals allows for identification of the frequency signal present in the data. The spectrum of the selected pass (Fig. 3-bottom) shows two strong peaks f_3 = 1.7348 Hz and f_6 = 3.4762 Hz, which indicate spin rate of the satellite. Due to 120° symmetry of the CCR array around the symmetry axis of the body and the specific number of CCR panels on the rings (3, 6, 9, 12) – the SLR data contains spectral signal which is defined by the spin rate multiplied by 3, 6, 9, 12 and combinations of these numbers. The peak f_3 is the 3rd harmonic of the spin rate and indicates a spin period of T = 3/1.7384 = 1.7257 s, while peak f_6 is the 6th harmonic: T = 6/3.4762 = 1.7260 s. The range of the investigated frequencies is limited by the Nyquist frequency (5 Hz), which is the half of the sampling frequency of the SLR system.

The frequency signal given by spectral analysis of the SLR data indicates an apparent spin of the satellite – which is a combination of spin rate of the body and an apparent effect caused by change of the station – satellite mutual orientation during the pass. In order to eliminate the apparent effect and obtain the true spin rate of the body we used simulations of the SLR measurements (Kucharski et al., 2007, 2008) to Ajisai.

The simulation model consists of two parts:

- macro-model, which contains information about station position in ITRF2000, and satellite position at given epoch time (calculated from predictions used for SLR: IRV, CPF).
- micro-model, which contains the coordinates of the CCR panels on the satellite, the range correction function (Fitzmaurice et al., 1977) and CCR energy transfer function (Arnold, 1979).

Ajisai is spinning around its symmetry axis and the orientation of the spin axis in the inertial reference frame is known (Kucharski et al., 2010b). In order to correct the apparent signal given by the spectral analysis a series of simulations are performed using the spin rate of the body as a parameter. During the simulated pass the spin rate is set to be constant and the range residuals are generated. The simulated dataset is then spectrally analyzed, and the obtained apparent frequencies are compared with the observed values. This process is repeated with different spin rates until the difference between the simulated and the observed apparent frequency achieves minimum. In such final case the parameter of the simulation indicates the inertial spin rate of the body.

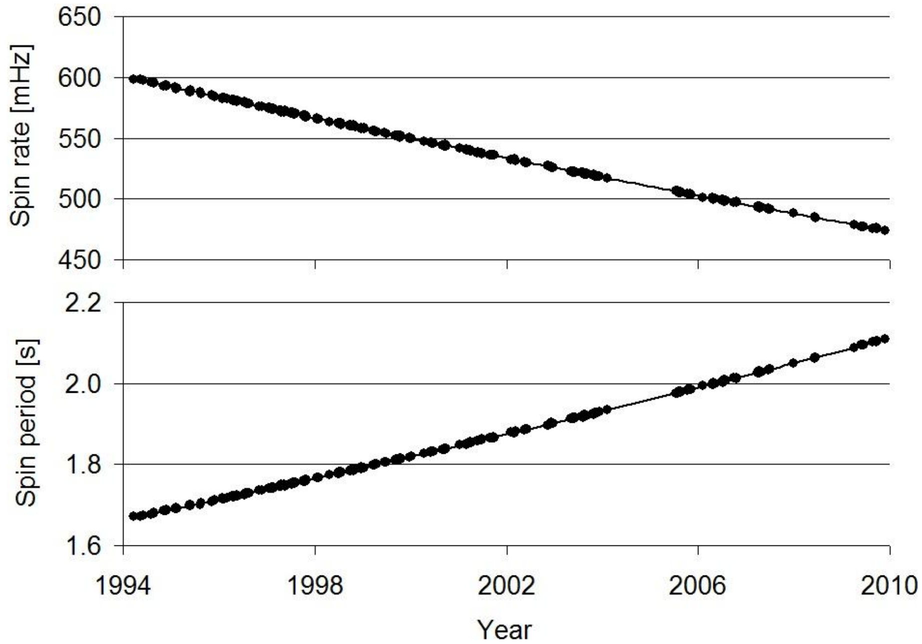

Fig. 4. Spin rate (top) and spin period (bottom) of Ajisai calculated from Borowiec SLR data. The values are approximated with exponential trend functions.

Fig. 4 presents spin rate and spin period values of Ajisai determined from Borowiec SLR data. The frequency peaks f_3 and f_6 are analyzed separately and together – as a single dataset $f_{3,6}$. The three data sets can be approximated with exponential trend functions, giving the following equations:

f_3) $f = 671.554058 \cdot \exp(-4.09491 \times 10^{-5} \cdot D)$ [mHz],
$T = 1.4890834 \cdot \exp(4.09491 \times 10^{-5} \cdot D)$ [s],

f_6) $f = 671.115907 \cdot \exp(-4.08324 \times 10^{-5} \cdot D)$ [mHz],
$T = 1.49005558 \cdot \exp(4.08324 \times 10^{-5} \cdot D)$ [s],

$f_{3,6}$) $f = 671.327761 \cdot \exp(-4.08849 \times 10^{-5} \cdot D)$ [mHz],
$T = 1.48958535 \cdot \exp(4.08849 \times 10^{-5} \cdot D)$ [s],

where $D=MJD-MJD_{Launch}$ is a day after launch. The obtained trend functions allow calculating the initial spin rate f_{ini} / spin period T_{ini} of the satellite at MJD_{Launch}; the accuracy of the method can be expressed as a RMS of the spin rate/period residuals calculated to the trend functions:

f_3) f_{ini} = 671.554, RMS = 0.358 [mHz]; T_{ini} = 1.48908, RMS = 0.00122 [s],
f_6) f_{ini} = 671.116, RMS = 0.203 [mHz]; T_{ini} = 1.49006, RMS = 0.0007 [s],
$f_{3,6}$) f_{ini} = 671.328, RMS = 0.238 [mHz]; T_{ini} = 1.48959, RMS = 0.00083 [s].

The obtained solutions coincide well with the 22 years trend function calculated from SLR data (all SLR stations) measured from August 14, 1986 to December 30, 2008 (Kucharski et al., 2009b), which gives f_{ini} = 671.778, RMS = 0.317 [mHz] and T_{ini} = 1.48859 s, RMS = 0.0007 s.

The spin rate residuals calculated from the Borowiec measurements to the 22 years trend function show the scale of the improvement caused by the apparent corrections. Table 1 presents the mean value and the RMS of the residuals calculated for the corrected and not corrected data sets.

Table 1. Mean and RMS of the Borowiec spin rate residuals calculated to the 22 years trend function; A: apparent values, I: inertial values (corrected for the apparent effects)

	Mean [μHz]	RMS [μHz]
$f_{3\text{-}A}$	437	391
$f_{3\text{-}I}$	-15	362
$f_{6\text{-}A}$	448	285
$f_{6\text{-}I}$	-28	244
$f_{3,6\text{-}A}$	439	333
$f_{3,6\text{-}I}$	-13	257

Correcting for the apparent effects lowers spin rate by more than 400 μHz and reduces RMS.

The three spin trend functions, obtained here, represent very similar results. The smallest RMS, however, comes from analysis of the f_6 signal, which is introduced by the arrangement of the CCRs on the rings around equator of the satellite. Due to large number of the CCRs distributed over the rings (Fig. 2: $R_{-2}..R_2$) the f_6 signal is more accurate than the f_3 – generated by the large gaps of the rings. Thus the results given by the f_6 peaks conclude this investigation.

4. CONCLUSIONS

Borowiec SLR system is capable to measure spin parameters of the fully passive Experimental Geodetic Satellite (Ajisai). The system operates with 10 Hz repetition rate laser and uses multi-photon sensitive PMT, what allows achieving high return rates (up to 80%) from Low Earth Orbiting satellites. Large amount of accurate range measurements collected during single pass delivers information about the spin rate of the satellite. Spectral analysis of Borowiec SLR data shows two frequency peaks f_3 and f_6 engraved by the spinning body to the data. The clear signal obtained from the 391 Ajisai passes measured from March 10, 1994 to November 27, 2009 shows en exponential slowing down of the satellite. This trend is mainly caused by the influence of the gravity and magnetic fields of the Earth. Small perturbations of the spin can be also caused by the non-gravitational effects, such as solar irradiation, Yarkovsky and Yarkovsky-Schach effects (Rubincam, 1988; Sengoku et al., 1995).

The long, 15 years, slowing down trend of Ajisai is a valuable source of scientific information for investigation of the forces and torques which are influencing its orbital motion. This information can help improving models of the perturbations used for precise orbit determination (POD) as well as help building the spin model of Ajisai, which is an important task for the planned laser time transfer via mirrors of this satellite (Kunimori et al., 1992).

5. REFERENCES

Andrés J. I., Noomen R., Bianco G., et al. (2004). Spin axis behavior of the LAGEOS satellites, J. Geophys. Res., 109 (B6), B06403.

Arnold D. (1979). Method of calculating retroreflector-array transfer functions, Spec. Rep., 382, Smithon. Astrophys. Obs., Cambridge, MA.

Bertotti B., Iess L. (1991). The rotation of LAGEOS, J. Geophys. Res., 96 (B2), pp. 2431–2440

Bianco G., Chersich M., Devoti R. et al. (2001). Measurement of LAGEOS-2 rotation by satellite laser ranging observations, Geophys. Res. Lett., 28(10), pp. 2113–2116.

Fitzmaurice M. W., Minott P. O., Abshire J. B. et al. (1977). Prelaunching testing of the Laser Geodynamic Satellite (LAGEOS), NASA Technical Paper 1062, NASA.

Kirchner G., Hausleitner W., Cristea E. (2007). Ajisai Spin Parameters Determination using Graz kHz Satellite Laser Ranging Data, IEEE Transactions on Geoscience and Remote Sensing, 45(1), pp. 201-205.

Kucharski D., Kirchner G., Schillak S., et al. (2007). Spin determination of LAGEOS-1 from kHz laser observations, Adv. Space Res., 39 (10), pp. 1576-1581.

Kucharski D., Kirchner G., Cristea E. (2008). ETALON spin period determination from kHz SLR data. Adv. Space Res., 42 (8), pp. 1424-1428.

Kucharski D., Kirchner G., Koidl F., et al. (2009a). 10 Years of LAGEOS-1 and 15 Years of LAGEOS-2 Spin Period Determination from SLR Data, Adv. Space Res., 43 (12), pp. 1926-1930.

Kucharski D., Kirchner G., Otsubo T., et al. (2009b). 22 years of Ajisai spin period determination from standard SLR and kHz SLR data, Adv. Space Res., 44 (5), pp. 621-626.

Kucharski D., Kirchner G., Otsubo T., et al. (2010a). The impact of solar irradiance on Ajisai's spin period measured by the Graz 2 kHz SLR system, IEEE Trans. Geosci. Remote Sens., 48 (3), pp. 1629-1633.

Kucharski D., Otsubo T., Kirchner G., Koidl F. (2010b). Spin axis orientation of Ajisai determined from Graz 2 kHz SLR data, Adv. Space Res., 46 (3), pp. 251-256.

Kucharski D., Kirchner G., Koidl F. (2011). Spin parameters of nanosatellite BLITS determined from Graz 2 kHz SLR data, Adv. Space Res., 48 (2), pp. 343-348.

Kunimori H., Takahashi F., Itabe T., et al. (1992). Laser ranging application to time transfer using geodetic satellite and to other Japanese space programs, in: Proceedings of the 8th International Workshop on Laser Ranging Instrumentation, Annapolis, NASA Conf. Pub. 3214, pp. 1-38–1-42.

Otsubo T., Amagai J., Kunimori H. (1998). Measuring Ajisai's spin motion, In Proc. 11th Int. Workshop on Laser Ranging, Deggendorf, Germany, pp. 674–677.

Otsubo T., Amagai J., Kunimori H. (1999). The center of mass correction of the geodetic satellite Ajisai for single-photon laser ranging, IEEE Trans. Geosci. Remote Sens., 37 (4).

Otsubo T., Amagai J., Kunimori H., et al. (2000). Spin Motion of the Ajisai Satellite Derived from Spectral Analysis of Laser Ranging Data, IEEE Trans. Geosci. Remote Sens., 38 (3), pp. 1417-1424.

Otsubo T., Appleby G. (2003). System dependent center-of-mass correction for spherical geodetic satellites, J. Geophys. Res., 108 (B4), 2201.

Otsubo T., Sherwood R. A., Gibbs P., et al. (2004). Spin motion and orientation of LAGEOS-2 from photometric observation, IEEE Trans. Geosci. Remote Sens., 42 (1), pp. 202-208.

Rubincam D.P. (1988). Yarkovsky thermal drag on LAGEOS, J. Geophys. Res. 93 (B11), 13805–13810.

Sasaki M., Hashimoto H. (1987). Launch and Observation Program of the Experimental Geodetic Satellite of Japan, IEEE Trans. Geosci. Remote Sens., GE-25 (5), pp. 526-533.

Sengoku A., Cheng M., Schutz B.E. (1995). Anisotropic reflection effect on satellite Ajisai, J. Geod. 70, 140–145.

Received: 2012-11-30,

Reviewed: 2012-01-07, by G. Kirchner,

Accepted: 2012-01-21.